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Damage Assessment of Aerospace Structural Components by Impedance Based Health Monitoring

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Abstract

This paper addresses recent efforts at the NASA Glenn Research Center at Lewis Field relating to the set-up and assessment of electro-mechanical (E/M) impedance based structural health monitoring. The overall aim is the application of the impedance based technique to aeronautic and space based structural components. As initial steps, a laboratory was created, software written, and experiments conducted on aluminum plates in undamaged and damaged states. A simulated crack, in the form of a narrow notch at various locations, was analyzed using piezoelectric-ceramic (PZT: lead, zirconate, titarate) patches as impedance measuring transducers. Descriptions of the impedance quantifying hardware and software are provided as well as experimental results. In summary, an impedance based health monitoring system was assembled and tested. The preliminary data showed that the impedance based technique was successful in recognizing the damage state of notched aluminum plates.

1. Introduction

Structural health monitoring (SHM) is an essential element of modern structural components. The idea of equipping structures with sensors and actuators in an attempt to impart "smartness" has great potential for establishing a cost effective, in-situ maintenance routine (Bhalla and Soh 2004). This is especially true for critical high performance, aerospace components where accessibility using traditional nondestructive evaluation techniques is limited (e.g., turbine propulsion components) or even impossible (e.g., long duration space exploration vehicles). Some examples of manual and time consuming nondestructive evaluation techniques (NDE), which are typically utilized off-wing in the aerospace industry, include eddy current, ultrasonic, fluorescent penetrant, magnetic particle, optical, and radiographic inspection (Winston et al. 2001). Regarding the cost effectiveness of reduced manual inspections, it is estimated that nearly 27 percent of an aircraft's life cycle cost is spent on inspections and repairs (Kessler et al. 2002). With an on-line, self actuated system such costs can be dramatically reduced. Furthermore, the impact of such an in-situ SHM system is that it not only increases safety and performance, but also enables converting schedule based into condition based maintenance, thus reducing both down time and costs (Bray and Roderick 1989).

The impedance based approach has demonstrated unique features that meet the requirements of an on-line SHM system. This form of structural health monitoring is based on the use of a sensor/actuator patch to obtain real-time and continuous measurements that reflect the health status of the monitored structure. This paper describes the development of an impedance based SHM system from hardware acquisition, to software development, to procedural methodology and, lastly, experimentation using undamaged and damaged aluminum plates.

2. Impedance Based Structural Health Monitoring

2.1 Theory

Impedance-based SHM uses piezoelectric (PZT: lead, zirconate, titarate) patches that are bonded onto or embedded in a structure. Each individual patch behaves as both an actuator of the surrounding structural area as well as a sensor of the structural response. The size of the excited area varies with the geometry and material composition of the structure. When a PZT material is subjected to an electric field it produces a mechanical strain, and when stressed it produces an electrical charge. For a PZT patch intimately bonded to a structure, driving the patch with a sinusoidal voltage sweep, for example, deforms and vibrates the structure. This is due to the patch applying a strain parallel to the structure's surface. In reaction to these elastic wave inputs, the structure produces a localized dynamic response. This dynamic response is transferred back to the PZT patch, which sequentially produces an electrical response that is analyzed in regard to the impedance behavior (Peairs et al. 2004). The structure's mechanical impedance is presented in the classical formulation as

$$Z_{str}(\omega) = i\omega m_e(\omega) + c_e(\omega) - ik_e(\omega)/\omega \tag{1}$$

The terms m_e, k_e, and c_e represent the structure's mass, stiffness, and damping coefficients while ω represents frequency. Due to mechanical coupling between the sensor and the host structure, this mechanical effect is picked up by the sensor and, through electro-mechanical coupling inside the active element, is reflected in the electrical impedance measured at the sensor's terminals. Figure 1 illustrates the basic concept (Giurgiutiu et al. 1998).

Solving the wave equation for the system shown in figure 1 yields the total impedance as measured by the PZT sensor, $Z(\omega)$, which contains both the structure's $Z_{str}(\omega)$and the sensor's $Z_{PZT}(\omega)$ impedances:

$$Z(\omega) = \left[i\omega C \left(1 - \kappa_{31}^2 \frac{Z_{str}(\omega)}{Z_{str}(\omega) + Z_{PZT}(\omega)} \right) \right]^{-1} \tag{2}$$

The term C denotes the zero-load capacitance, and κ_{31} represents the coupling coefficient of the piezoelectric active sensor for in-plane vibration. At this point in time, the impedance based health monitoring technique is typically utilized as an empirical before-and-after tool that identifies changes in the damage state by noting phase shifts or magnitude alterations in the measured impedance as compared to a base line measurement.

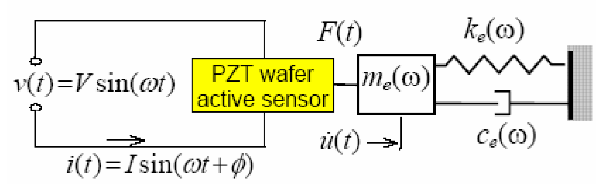

Figure 1.—Electro-mechanical coupling between the active sensor and the structure (Giurgiutiu et al. 1998).

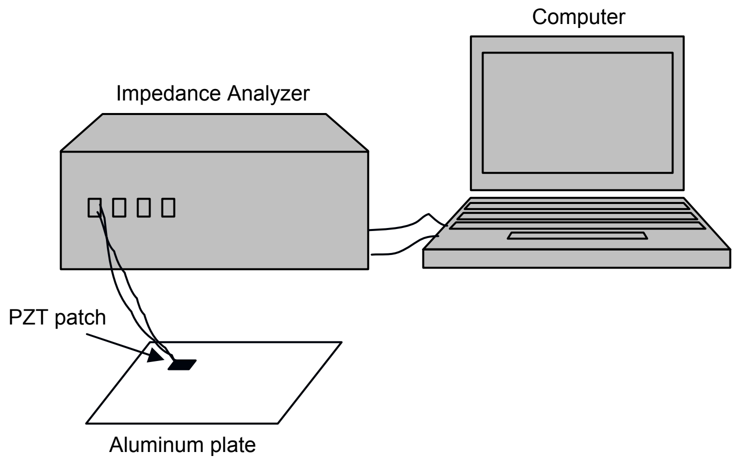

Figure 2.—Experimental setup.

2.2 Experimental Set-up

Figure 2 shows the experimental set-up utilized for capturing electromechanical (E/M) impedance data. The E/M impedance data were taken using an HP 4194A impedance analyzer connected to a computer via the GPIB interface. A custom software program was developed for control of the impedance analyzer functions as well as acquisition, processing and display of the collected data. Of particular importance was the ability to modify the frequency sweep range, step size, excitation voltage, and equivalent circuit mode (series or parallel) for a given test. For each test, impedance data were acquired at every discrete excitation frequency within the sweep. In this study, only the real portion of the impedance was collected and analyzed as this has been shown to be the most sensitive in regard to damage identification (see Kabeya 1998). Following data acquisition, the software provided functions for displaying collected data, averaging, performing damage metric calculations and exporting raw and reduced data.

2.3 Damage Metric

In order to quantify damage, a metric was employed that examines the change in the E/M impedance response in regard to the baseline condition. This damage metric, D, is expressed as

$$D = (1 - \rho)^2 \tag{3}$$

where,

$$\rho = \frac{\mathrm{cov}(XY)}{\sigma(X)\sigma(Y)} \tag{4}$$

The term ρ represents the correlation coefficient concerning the baseline, (X), and damaged, (Y), E/M impedance responses. It is a function of the covariance, cov(XY), and standard deviations, $\sigma(X)$ and $\sigma(Y)$, of the response values (Miller and Freund 1985). The damage metric will range from 0 for the undamaged case to 1 for fully damaged case (i.e., no correlation between the before-and-after impedance measurements). Similar approaches have been utilized in other studies (e.g., Giurgiutiu et al. 1998).

3. Experimental Procedure

A series of experiments on two, simple geometry specimens (thin-gage aluminum square plates) were conducted for assessing the potential of the impedance based health monitoring system. The plate specimens, each measuring 100×100-mm with a thickness of 1.5-mm, were made from 6061-T6 aluminum alloy sheet. Each plate was instrumented with one 10×10-mm PZT patch (material PSI-5A4E, thickness 0.19-mm attached using cyanoacrylate adhesive) purposely located at a vibration-sensitive location. This location was determined by conducting a finite element analysis focusing on the modal response of the plate and placing the patch in an area suspect to maximum displacements. After capturing baseline data for each of the undamaged plates, a single 10-mm straight, through-thickness EDM notch (0.3 mm width) was utilized to simulate a crack. The notch locations for each plate are shown in figure 3. As was the case for the patch placement, the notches were located in areas of maximum displacement as defined by the finite element analyses. During the experiments, the specimens were supported on foam to simulate free-free conditions.

Preliminary tests were conducted to determine the frequency range best suited for measuring the damage dependent changes in the impedance response. Impedance values were collected for 15 repetitions over a 20 to 200 kHz frequency range for each specimen in the undamaged state. The 15 repetitions were then averaged (i.e., a single impedance plot using the 15 repeats) and compared to one of the 15 samples (randomly chosen) from within the same data set. This was done for each of the two plates. The intent was to look for a frequency window that produced the best repeatability regarding the 15 measurements in the undamaged state by avoiding noisy frequency regions that lack consistency between measurements. To this end, the damage metric was calculated for a 10 kHz wide, sliding window starting at 20 kHz and ending at 200 kHz. The step size for the window and the accompanying damage calculation was 1 kHz.

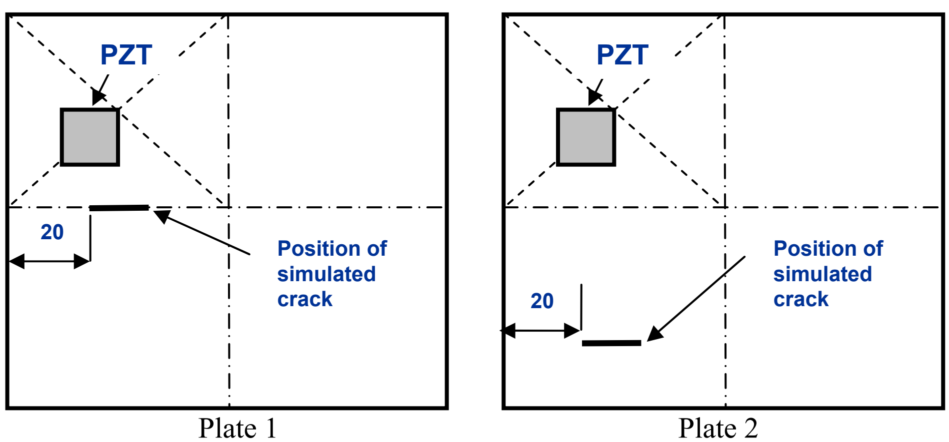

Figure 3.—Schematic of specimens with simulated cracks and PZT sensors.

4. Results

Figure 4 shows a plot of the damage metric versus the central frequency for the windowed region regarding the undamaged plates. As mentioned above, this procedure was done in order to search for frequency regions that offered good repeatability under constant conditions (i.e., undamaged case). It can be seen from this plot that the damage metric was consistently valued at zero from 20 kHz to approximately 45 kHz, meaning that the two plots correlate well in that frequency range. The damage metric, in regions of good repeatability, should be close to zero, since the material state was maintained (zero damage in this case). Beyond 45 kHz, however, there was a noticeable inconsistency regarding the damage parameter. Based on these results, a frequency range of 20 to 40 kHz was chosen for subsequent E/M impedance measurements.

Next, a comparison was made between the baseline of plate 1 and the baseline of plate 2. Figure 5 shows the E/M impedance plots as well as indicating the damage parameter value based on the correlation of the two plates (eq. (3)). Each of the impedance plots was an average of 15 repetitions. The damage metric (D = 0.965) indicated that there was much discrepancy between the two baseline measurements. As stated earlier, the large specimen to specimen variations dictate that the method be utilized as a comparison of baseline and subsequent measurements within the same specimen. Similar observations were made by Winston et al. 2001.

Figure 6 shows the results of comparing the baseline and the notched (i.e., damaged) cases for plate 1. The presence of the notch did modify the frequency response function. This was indicated by the shifting of the resonant frequencies and by the appearance of new resonances. The calculated correlation coefficient for this case was $\rho = 0.497$, and the damage metric was D = 0.253 based on eq. (3). Next, figure 7 shows the results for plate 2 comparing the undamaged baseline with the damaged case, again, calculated using 15 repetitions for each plot. The correlation coefficient for plate 2 was $\rho = 0.365$, and the damage metric was D = 0.403. Note that plate 2 before-and-after notch comparisons showed a larger damage metric as compared to the plate 1 case, even though the plate 2 notch was located farther from the PZT patch. At this point there is no explanation for this behavior, although, the uniqueness of the plate to plate behaviors probably plays a part. Furthermore, the changes in the E/M impedance could also be influenced by the notch location as it relates to the plate's vibration displacement response and node locations. Further research needs to be conducted concerning these results.

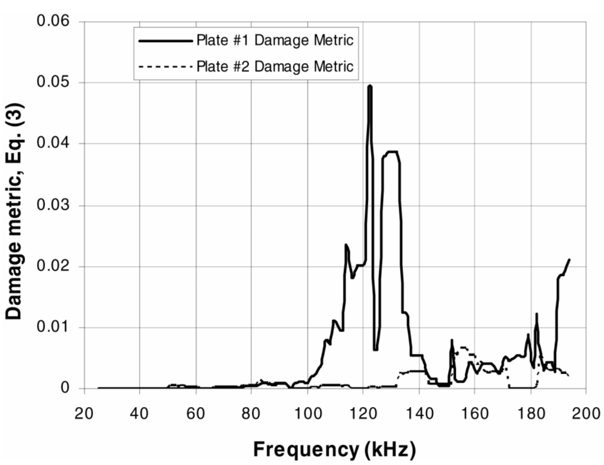

Figure 4.—Windowed correlation coefficient (20 to 200 kHz, 10 kHz window, 1 kHz step) for two uncracked plates.

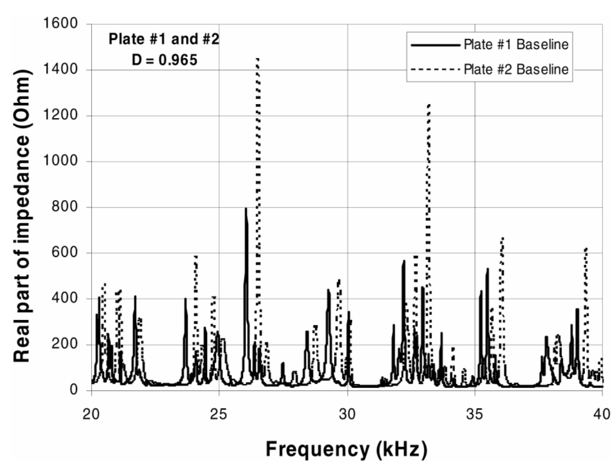

Figure 5.—Comparison of undamaged plates 1 and 2 (20 to 40 kHz). Damage metric, D, was 0.965 indicating a lack of correlation between the two plates.

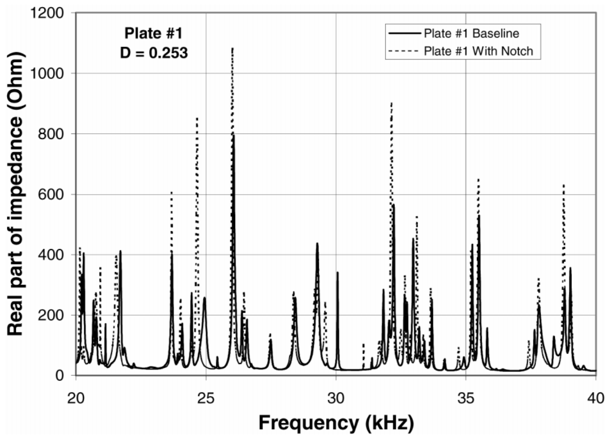

Figure 6.—Averaged E/M impedance results for plate 1 with and without a notch.

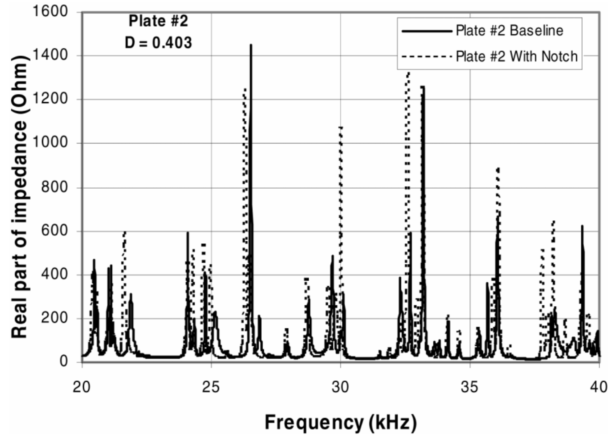

Figure 7.—Averaged E/M impedance results for plate 2 with and without a notch.

5. Conclusions

This study was conducted in order to establish an impedance based structural health monitoring laboratory, which included both the acquisition of hardware and the development of software, as well as conducting preliminary experiments on aluminum plates in undamaged and damaged states. In addition, a methodology was developed that defined the frequency range utilized for the E/M impedance measurements. This was based on finding frequency ranges that offered the best repeatability (i.e., lowest noise) as expressed by either a high correlation or low damage value. Next, simulated cracks, in the form of narrow notches, were analyzed using PZT patches as impedance measuring transducers. Conclusions from the experiments on the two aluminum plates were as follows: The assessment of the impedance behavior regarding the two undamaged plates indicated that variations between specimens overrode changes due to damage. Therefore, it was shown that the impedance method was best utilized as a comparison of baseline and subsequent measurements concerning the same specimen. Next, the E/M impedance measurements were able to recognize the changes between the undamaged and damaged (i.e., notched) cases for each plate, although, larger changes were observed for plate 2 even though the notch was located farther from the PZT patch as compared to plate 1. This may have been due the uniqueness of the plate to plate behaviors, as well as the influence of notch and patch locations as it relates to the plate's displacement response and node locations. Further research is needed regarding this observation.

With the establishment of the hardware and software as well as success concerning the preliminary experiments, the system will be further tuned to the various material systems (e.g., composites or thermal protection system materials) and structures that are of most interest to NASA. This includes the application of the technique to rotor components (either aero or space propulsion) by utilizing slip ring connections. In addition, in cooperation with the Virginia Polytechnic Institute and State University, research is being conducted regarding wireless and self powering applications especially relating to space exploration vehicles. Lastly, the same PZT patches can be utilized as ultrasonic transducers, thereby creating a layered health monitoring system that is permanently attached to a structure allowing for continuous feedback regarding system health.

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13. ABSTRACT ***(Maximum 200 words)***

This paper addresses recent efforts at the NASA Glenn Research Center at Lewis Field relating to the set-up and assessment of electro-mechanical (E/M) impedance based structural health monitoring. The overall aim is the application of the impedance based technique to aeronautic and space based structural components. As initial steps, a laboratory was created, software written, and experiments conducted on aluminum plates in undamaged and damaged states. A simulated crack, in the form of a narrow notch at various locations, was analyzed using piezoelectric-ceramic (PZT: lead, zirconate, titarate) patches as impedance measuring transducers. Descriptions of the impedance quantifying hardware and software are provided as well as experimental results. In summary, an impedance based health monitoring system was assembled and tested. The preliminary data showed that the impedance based technique was successful in recognizing the damage state of notched aluminum plates.

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